Advances in tensiometer-based suction control systems

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ABSTRACT: Cunningham (2000) and Jotisankasa (2005) pioneered the development of tensiometer-based suction control systems. In these systems, wetting and drying of the soil are achieved by water injection and circulation of air in contact with the specimen while suction is monitored by sample-mounted high suction tensiometers. Unlike the axis translation technique, these systems avoid using elevated air pressures and better reproduce the drying and wetting conditions occurring in the field. Building upon these earlier works, this paper describes an automated tensiometer-based suction control system that enables direct measurement of water content changes inside the sample. A diaphragm pump forces air to flow inside a closed loop that runs across the sample while a moisture trap ensures that the relative humidity of the circulating air is kept low. As the circulating air dries the soil, the amount of abstracted water is measured by continuous weighing of the desiccant inside the moisture trap. Wetting of the sample is instead achieved by controlled injection of water through a solenoid valve connected to a pressurized volume gauge. The changes of soil water content are given by the difference between the amounts of water injected by the volume gauge and that retained by the desiccant. The system is used to impose cycles of drying and wetting on compacted clayey specimens and results from preliminary tests are presented.

1 SUCTION-CONTROLLED TESTING OF UNSATURATED SOILS

The selection of an appropriate suction control technique for testing unsaturated soil samples depends on the range and type of suction (i.e. total or matric) to be controlled.

Conventional techniques for controlling suction in unsaturated soils (e.g. axis translation, osmotic flow and vapour equilibrium) allow direct imposition of suction at the boundary of the sample. In recent years, however, alternative techniques have been developed to provide indirect control of suction or water content. These use a computerized feedback system that includes a device to measure pore pressure or water content and a control device to impose wetting or drying. Software is usually employed to compare measurements with target values and activate control as required. The feedback system continuously adjusts the control device to maintain the measured variables within a set tolerance of the target.

In the suction control system presented in this paper, the measurement devices are: a) a sample-mounted tensiometer for measuring pore water pressure on the specimen surface, b) a continuously weighted moisture trap for measuring removal of water from the system and, c) a pressurized volume gauge for measuring addition of water into the system. Controlled wetting or drying of the sample is achieved by forced circulation of dry air or direct injection of liquid water inside a closed loop that runs across the sample.

Unlike the axis translation technique, the proposed system does not require application of elevated pore air pressures. It therefore ensures testing conditions that closely resemble those existing in the field allowing development of negative pore water pressures below the water cavitation threshold. The use of sample-mounted high suction tensiometers provides direct measurements of negative pore water pressures on the sample surface. This overcomes limitations due to the indirect nature of suction measurements in the osmotic and vapour equilibrium techniques, where suction is correlated to the chemical concentration of a control fluid or to the relative humidity in equilibrium with a saline solution.

Cunningham (2000) and Jotisankasa (2005) were the first to develop a suction control system for laboratory testing of unsaturated soils based on circulation of air along the sample surface and direct suction measurement by sample-mounted miniature tensiometers.

The suction range of these systems depends on type and pre-conditioning of the high suction tensiometer employed but it can typically cover negative pore pressures down to -1.5 MPa, which is adequate for most geotechnical engineering applications. This contribution initially reviews two tensiometer-based systems developed by Cunningham (2000) and Jotisankasa (2005) to control drying or wetting of the sample by means of air circulation. It then describes an enhanced suction control system, which has been developed in the present work. The enhanced system operates along similar lines as those of previous proposals but incorporates modifications to improve measurement of sample water content and effectiveness of drying or wetting.

2 PREVIOUS TENSIOMETER-BASED SUCTION CONTROL SYSTEMS

Cunningham (2000) was the first to develop a tensiometer-based system that employed air circulation for controlling suction in triaxial tests (Figure 1).

The system was only able to dry the soil and it could therefore be employed for the application of constant suction stress paths only if pore water pressure showed a tendency to increase during loading at constant water content. The system used two sample-mounted tensiometers to read suction at the side and at the top of the specimen. Air was circulated along the base of the sample by applying a positive pressure at one end of the cell pedestal while leaving the other end open to atmosphere. A spring valve, placed in the tubing, automatically opened when air pressure exceeded a given value. The system also included a transducer to monitor pressure inside the air line. If the average pore water pressure measured by the top and mid-height tensiometers was higher than the target value, the control software would automatically open the spring valve by raising the line pressure so that air would start flowing and the sample would start drying. When pore water pressure dropped back within a set tolerance of the target, the control system would lower air pressure again to close the valve and stop air circulation leaving the sample to equalize.

Jotisankasa (2005) further developed the system designed by Cunningham (2000) through incorporation of a relative humidity sensor at the outlet of the air line and by extending the system to impose wetting as well as drying (see Figure 2). The system developed by Jotisankasa (2005) was also able to control suction automatically at a target value.

Similarly to Cunningham (2000), the system developed by Jotisankasa (2005) for soil drying imposed air circulation along the base of the sample and used two tensiometers to measure pore water pressures at two different points on the surface of the sample (see Figure 2a). Changes of water content were estimated by comparing measurements of relative humidity at the outlet and inlet of the air line running along the sample base.

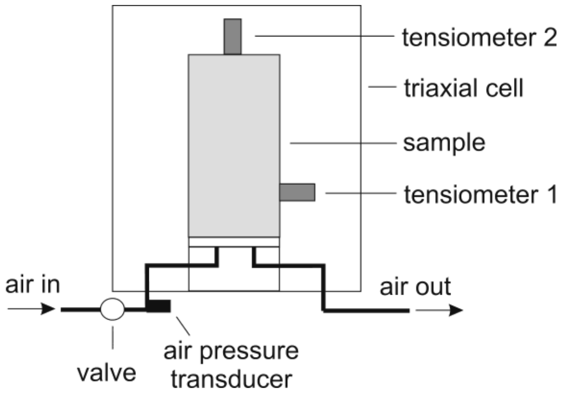


Figure 1 Drying system by Cunningham (2000)

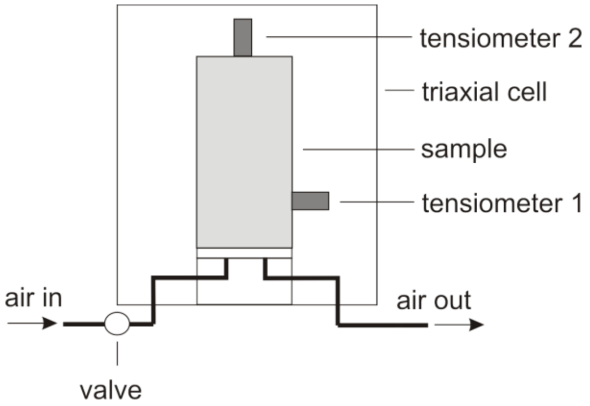
Wetting was initially based on the circulation of moist air but, as this proved ineffective, it was subsequently replaced by direct injection of liquid water (see Figure 2b). Water was manually injected in stages at the top of the sample by using a peristaltic pump. After each injection, the readings of suction and strains were monitored until stable values were achieved before moving to the next injection stage.

3 NEW TENSIOMETER-BASED SUCTION CONTROL SYSTEM

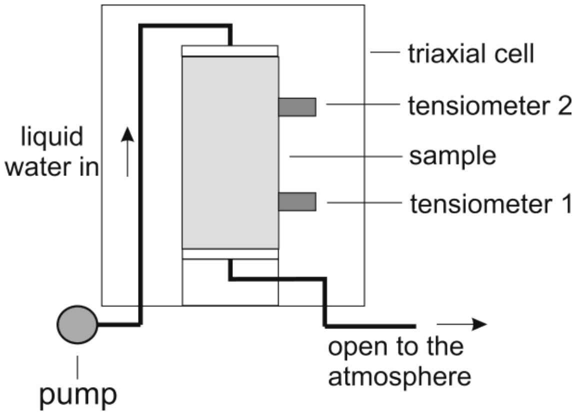
3.1 *General set-up*

The suction control system here proposed is similar to those developed by Cunningham (2000) and Jotisankasa (2005) but includes additional features to improve effectiveness of air circulation during drying or wetting and to provide more accurate measurements of the changes of the soil water content.

The proposed system was developed for controlling suction during triaxial tests but could be adapted for use with other types of equipment, such as oedometers or shear boxes. A schematic representation of the system is presented in Figure 3, which shows that a single high suction tensiometer is used to measure pore water pressures at the base of the sample. The high suction tensiometers used in this work were designed by Durham University and Wykeham Farrance Limited (Lourenço et al., 2006) and were able to read minimum values of pore water pressure between -1.5 MPa and -2 MPa.



(a)



(b)

Figure 2. System by Jotisankasa (2005); a) drying, b) wetting.

Comparison of Figures 1, 2 and 3 indicates that the proposed experimental set-up differed from previous systems because air was circulated inside a closed loop running through the entire sample rather than across an open line at the specimen base. During drying, relative humidity inside the closed loop was kept low by means of a moisture trap containing silica gel (a commonly used laboratory desiccant) through which air flowed. During wetting, controlled amounts of liquid water were injected inside the air circulation loop while the moisture trap avoided condensation in the tubes. The adoption of a closed air circulation loop, such as that shown in Figure 3, achieved a twofold objective of maximizing the sample surface exposed to air flow while, at the same time, isolating air circulation from the surrounding environment. In this way, changes of sample water content could be evaluated by measuring the respective amounts of water captured by the moisture trap and injected by the volume gauge. A hygrometer was also placed in the loop to measure the relative humidity of the circulating air.

An automated feedback system using the software TRIAX (Toll, 1999) was employed to impose suction controlled stress paths to the sample. Manual control could be alternatively adopted by relying on a person to take measurements and operate the control devices.

In addition to controlling pore water pressure, the computerized triaxial system could also impose target values of confining pressure, vertical load and water content while measuring air pressure, volumetric strain and axial strain in a fully automated way. The system included a double walled triaxial cell to measure sample volume changes during tests on unsaturated soils.

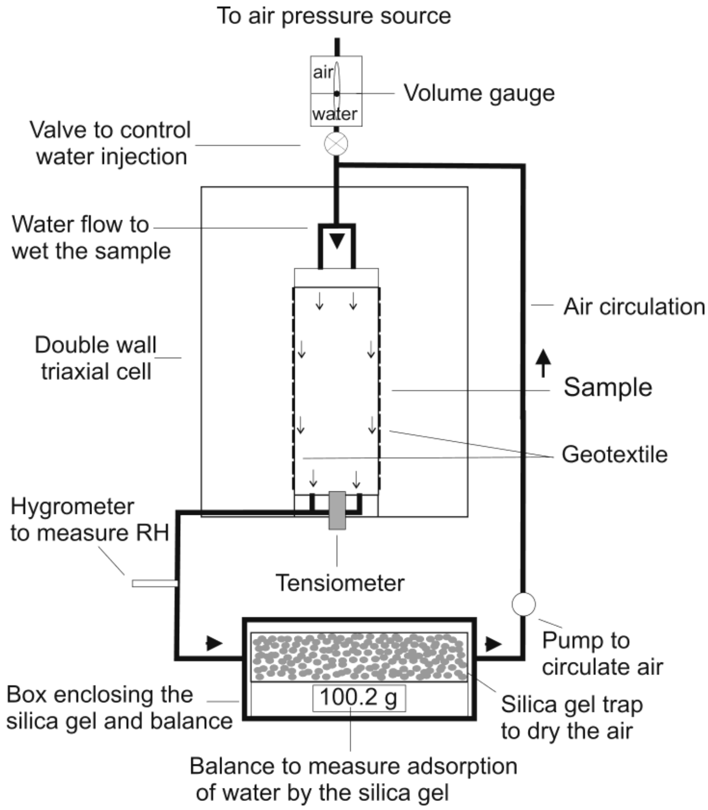


Figure 3. System for drying and wetting of soil samples

3.2 *Drying control*

During drying, air at low relative humidity was circulated inside the closed loop shown in Figure 3 without water injection.

The moisture trap ensured that water vapour was continuously removed from the circulating air so that relative humidity was kept low and drying potential remained high. The moisture trap consisted of granular silica gel (with an approximate dry mass of 400g) continuously weighted by a digital balance sealed inside an air-tight metal box, which was connected to the air circulation loop (see Figure 3). By assuming that all water removed from the sample is captured by the silica gel, it was possible to relate any increase in weight registered by the digital balance to a decrease of soil water content.

The moisture trap proved particularly efficient in drying the air due to the high specific surface area of the silica gel. Figure 4 shows the results from a preliminary experiment carried out on a sample of approximately 400g dry silica gel left exposed to the laboratory atmosphere at an ambient relative humidity of about 55% over a period of several days. Figure 4 indicates that the water absorption rate decreased with time as the silica gel came into equilibrium with the environmental humidity after an increase in weight of approximately 32g (corresponding to a water content of about 8%). This experiment confirmed that relatively small amounts of silica gel could effectively remove vapour from the surrounding air even when exposed to a lower relative humidity than that existing inside the air circulation loop of the proposed suction control system.

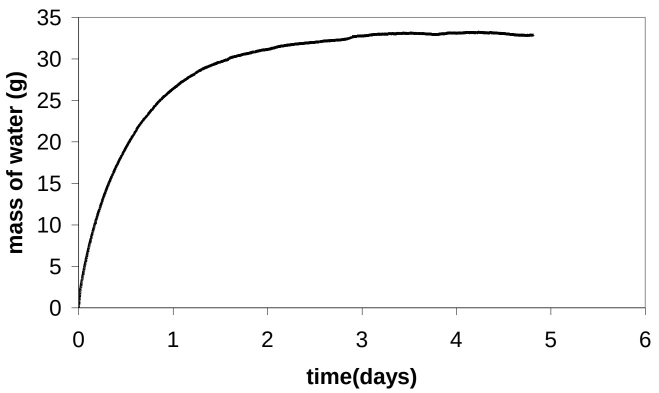


Figure 4: Adsorption of water by approximately 400g of initially dry silica gel at an ambient relative humidity of about 55%.

Some difficulties were encountered in making the metal box of the moisture trap completely vapour leak-proof. In one experiment, about 785g of dry silica gel was placed on the balance and sealed in the air-tight metal box with all connections shut. Despite taking precautions to prevent leakage of vapour into the box from the outside environment, the moisture absorbed by the silica gel increased with time with an apparently linear trend (see Figure 5). This, however, does not pose an insurmountable problem as long as the leakage rate is reasonably constant over time and can therefore be calibrated.

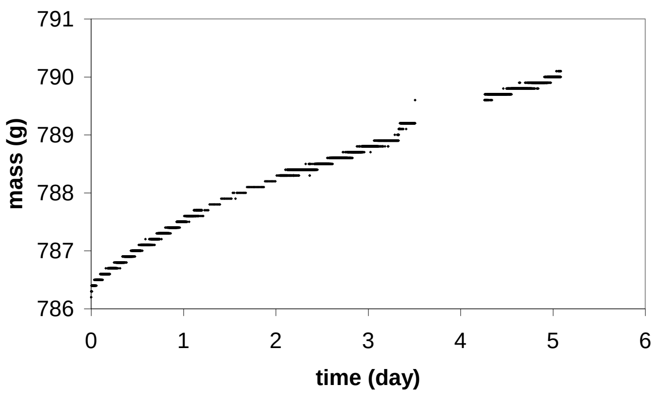


Figure 5. Leakage though moisture trap metal box.

A diaphragm pump was used to force air around the loop running across the sample and the moisture trap. Unlike the previous systems proposed by Cunningham (2000) and Jotisankasa (2005), where air was pumped along the specimen base, flow was imposed in this case across the entire sample height to maximize soil exposure to drying and to avoid large spatial variations of pore water pressure across the height of the specimen.

During initial tests, it was evident that a large difference of pore air pressure could occur between the two extremities of the sample depending on the sample air conductivity, which is in turn controlled by the intrinsic permeability and degree of saturation of the soil. This is of course undesirable as it creates a variable net stress field across the height of the sample. In order to ease flow and to reduce pore air pressure gradients, geotextiles were subsequently placed between the lateral surface of the sample and the latex membrane (Figure 3).

Controlled drying was achieved by setting a target value for the pore water pressure measured by the tensiometer at the bottom of the sample. The software TRIAX automatically activated the pump, initiating flow of dry air, when pore water pressure rose above target and stopped air circulation when pore water pressure dropped below target. Figure 6 shows a typical test performed on a sample of compacted sandy clay, which was dried to a target pore water pressure of -300 kPa from an initial almost saturated condition while subjected to a cell pressure of 300 kPa. Once the measurement of pore water pressure reached the target, the control software continued switching the pump on or off as the pressure read by the tensiometer became either higher or lower than target (within a set tolerance of 1 kPa). Given that tensiometer readings did not respond immediately to the activation or deactivation of air flow, the measured pressure often exceeded the set tolerance band by few kPas. Nevertheless, the degree of control still appears of acceptable accuracy.

Figure 6 also shows that the periods of the subsequent pressure cycles increased as the soil water content stabilized at the target pore water pressure of -300 kPa, signifying a progressive equalization across the sample.

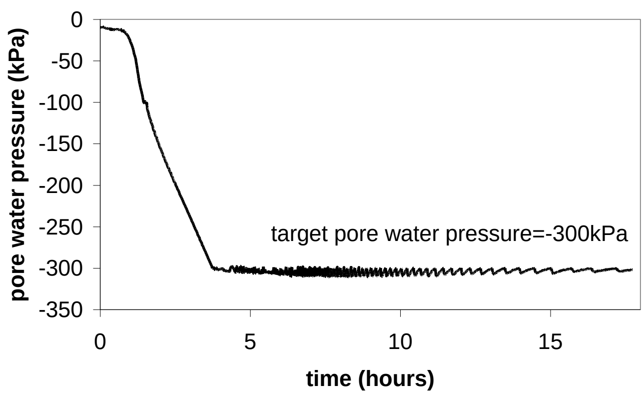


Figure 6: Automatic drying to a pore water pressure of -300 kPa.

3.3 *Wetting control*

An initial attempt was made to wet the soil by circulation of humid air but this proved unsuccessful as the sample tended to become drier rather than wetter. In addition, significant condensation occurred in the tubing, which made impossible to quantify accurately the amount of water retained by the sample.

Because of these difficulties, it was then decided to wet the sample by automatic injection of liquid water into the air circulation loop through a solenoid valve connected to a pressurized volume gauge. The solenoid valve was opened at regular intervals so that consecutive water pulses of approximately 0.05 cm^3 were introduced from the pressurized volume gauge into the loop. Air was circulated to help distribution of water on the sample surface and to facilitate moisture adsorption by the soil. The moisture trap avoided condensation or accumulation of water inside the tubes during wetting. Any change of soil moisture was then quantified as the difference between the water injected by the volume gauge and that retained by the moisture trap. The silica gel acted as a sink preventing storage of unaccounted moisture inside the system, hence ensuring that the any difference between injected and retained water could be entirely attributed to changes in the sample moisture content.

A typical wetting-drying cycle is shown in Figure 7, where a sample of compacted sandy clay was initially wetted to a target pore water pressure of -200 kPa and then dried back to a target pore water pressure of -400 kPa, while subjected to a cell pressure of 300 kPa.

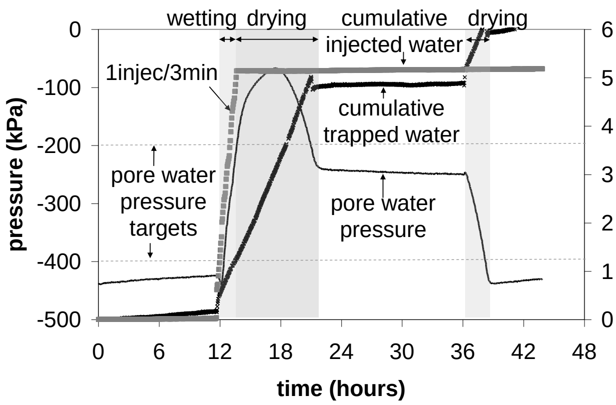


Figure 7. Automatic wetting and drying cycle.

As water injection progressed at a rate of one pulse every three minutes, air was continuously circulated from the top to the base of the sample and into the moisture trap along the closed loop shown in Figure 3. Figure 7 indicates that the pore water pressure measured at the base rose while water injection took place (see light grey shadow in Figure 7).

As soon as pore water pressure reached the target of -200 kPa, water injection was stopped but pressure kept on rising overshooting the target by more than 100 kPa. Circulation of dry air was maintained while the target had been overshot (see dark grey shadow in Figure 7), forcing eventually the soil to dry and the pore water pressure to be corrected back towards the target. Air circulation was stopped as soon as the tensiometer read a value of -200 kPa but, again, this did not prevent the pressure from reducing further, hence undershooting the target.

Pore water pressure eventually stabilized at approximately -250 kPa and air circulation was then started again to dry the sample to a pressure of -400 kPa. Once more, the reading of the tensiometer undershot the target by about 50 kPa despite air circulation had been stopped as soon as the pressure target had been achieved.

The results observed during the drying path in Figures 6 are somewhat different from those observed during the drying paths in Figure 7. In the former case, the measured pore pressure never significantly undershot the target while this is not true for the drying paths shown in Figure 7. In both instances, air circulation was stopped when a water pressure equal to the target was measured at the base of the sample. In the test shown in Figure 6, however, air was circulated from the base to the top of the sample while, in the test shown in Figures 7, air was circulated in the opposite direction. Hence, in the latter case, pore water pressure was highest at the base because the above soil had been exposed to drier air coming from the top. This would explain the decrease of pore water pressure at the base as pore water pressure tended to equalize throughout the soil mass following the end of air circulation.

It was also found that wetting was much more difficult to control than drying and target pressures were overshot by a large margin during wetting regardless of the direction of air flow and the location where pore water pressure was measured.

Figure 7 also shows the two curves giving the cumulative amounts of water injected by the volume gauge and absorbed by the moisture trap. Assuming no external water losses or gains, the variation of water content inside the sample at equilibrium could be measured as the difference between these two curves.

4 CONCLUSIONS

The paper presents a computerized system that uses automated air circulation and water injection to control suction during triaxial tests on unsaturated soil samples. Unlike the axis translation technique, the proposed method does not require application of elevated air pressures and enables development of negative pressures inside the soil pores, which closely replicates real field conditions. In addition, unlike other suction control techniques where pore air is maintained at atmospheric pressure, pore water pressures are not correlated to relative humidity or osmotic pressure but they are directly measured by a miniature tensiometer at the base of the sample.

This work extends the suction control systems previously developed by Cunningham (2000) and Jotisankasa (2005). It introduces additional features to improve measurement of water content changes inside the sample and to enhance effectiveness of drying and wetting. In the present system, air is circulated inside a closed loop across the height of the sample rather than across an open line at the specimen base. A moisture trap is incorporated within the air circulation loop to keep relative humidity low during drying and to avoid water condensation during wetting. A new approach is also employed to obtain continuous measurements of injected water volume and water mass absorbed by the moisture trap. Changes in the sample water content are evaluated as the difference between these two measurements.

Drying or wetting of the sample is governed by means of a computerized feedback routine, which commands air circulation and water injection based on the comparison between measured and target values of pore water pressure.

Results from initial wetting and drying tests on compacted clay samples are presented to demonstrate the performance of the proposed suction control system. The system is capable of accurately imposing drying of the sample to a target suction level. However, the inertia of wetting paths is more difficult to control and, when pore water pressure is increased, the target is often overshot by a significant amount.

Further research is required to devise a wetting control method that is not only capable of increasing the pore water pressure but also of accurately halting or reversing the pressure trend at any point during the imposed wetting path.

Although the suction control system presented in this paper was specifically designed for use inside a triaxial cell, similar principles could be equally employed for controlling suction in other testing equipment such as oedometers or shear boxes.

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